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Multi-Antenna Communications over Rapidly Fading Channels Estimation and Space-Time Coding
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The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

S1. Research Quality Indicators

- a. PI (Georgios B. Giannakis) received the **2001 Best Paper Award** from the IEEE Signal Processing Society for the paper reporting research supported by this grant. The paper-award citation is:

N. D. Sidiropoulos, R. Bro and G. B. Giannakis, "Parallel Factor Analysis in Sensor Array Processing," *IEEE Transactions on Signal Processing*, Vol. 48, No. 8, pp. 2377-2388, August 2000.

- b. PI (Georgios B. Giannakis) received the **2000 Best Paper Award** from the IEEE Signal Processing Society for the paper reporting research supported by this grant. The paper-award citation is:

A. Scaglione, G. B. Giannakis, and S. Barbarossa, "Redundant Filterbank Precoders and Equalizers, Parts I & II" *IEEE Transactions on Signal Processing*, vol. 47, pp. 2007-2022, July 1999.

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- c. PI (Georgios B. Giannakis) received the **IEEE SP Society's Technical Achievement Award** which honors a person who, over a period of years, has made outstanding technical contributions to the theory and/or practice in technical areas within the scope of the Society, as demonstrated by publications, patents, or recognized impact on the field. His award citation reads:

"For fundamental contributions to non-Gaussian and non-stationary signal analysis, system identification, and equalization of single- and multi-user communication systems."

- d. A total of six Ph.D. students and one postdoctoral researcher worked under this grant over its 3yr period. Three that graduated now hold faculty (asst. prof.) positions:

Dr. Anna Scaglione	(Cornell University)
Dr. Cihan Tepedelenlioglu	(Arizona State University)
Dr. Zhiqiang Liu	(University of Iowa)

S2. The work in this grant provided fundamental results in the development of the now popular Space-Time Coding Techniques that have been recognized as effective means of boosting the capacity and performance of multi-antenna communication systems. The PI continues his research on Space-Time Coding that is now also supported by ARL's Collaborative Technology Alliance (CTA) on Communications and Networking under grant: DAAD19-01-2-011.

The research in the present ARO grant indeed layed the groundwork for the research efforts supported by the ARL/CTA.

S3. This report supplements our report filed in August 2000.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12 b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This 3-year project dealt with development and testing of efficient algorithms for modeling, and (blind) estimation of time-varying communication channels, and the resulting (self-recovering) antenna receivers and equalizers in rapidly fading mobile battlefield scenarios. Highlights of recent results include space-time coded transmit- and receive-diversity to combat noise, oscillator drifts, and Doppler effects; optimal wedding of beamforming with space-time coding; space-time-frequency coding for use over frequency-selective channels; space-time-Doppler coding for time-selective channels; and optimal training over doubly-selective channels.			
14. SUBJECT TERMS Multi-antenna Communication Systems, Space-Time Coding, Fading, Multipath, Time-Selectivity, Frequency-Selectivity, Mobility High-Rate Systems, Multi-Carrier Systems, OFDM, CDMA Channel Estimation, Blind Equalization, Training, Differential Encoding, Linear Precoding, Channel Coding, Turbo-Decoding			15. NUMBER OF PAGES
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Main Results:

1. A Basis Expansion Model of Rapidly Varying Channels

We developed finitely parameterized basis expansions for single-input single-output (SISO) time-varying (TV) channels equivalent to multivariate time-invariant (TI) channels with inputs formed by modulating a single input with the bases. SISO-TV fading channels are of paramount importance both for commercial as well as for military communications because they capture phase noise, oscillator drifts, Doppler effects caused by relative motion between transmitters and receivers, and varying multipath propagation encountered with mobile wireless links in the battlefield. They cause time- and frequency-selective intersymbol interference (ISI) which has been traditionally modeled via random (Rayleigh or Rician) channels; however, by establishing links with existing physical channel measurements, we have shown that deterministic Fourier bases expansions are well motivated for modeling rapidly fading mobile communication channels when multipath propagation caused by a few dominant reflectors gives rise to (Doppler induced) linearly varying path delays.

2. Estimation and Equalization of Time-Varying MIMO Channels

We developed algorithms that estimate Doppler frequencies blindly using cyclic statistics and determine the channel orders relying upon rank properties of a received data matrix. By complementing channel (or Doppler) diversity with temporal, or, spatial diversity (available with oversampling or multiple antennas), we have derived blind estimators of TV channels along with direct equalizers under with minimal (persistence-of-excitation) assumptions on the input and the bases. Two deterministic blind equalization algorithms have been derived: one determines the channels first and then the equalizers, whereas the other estimates the equalizers directly. The equalizers are time-invariant, multivariate, zero-forcing, and lend themselves to optimally weighted and adaptive extensions. We have also proved that exploitation of the input's whiteness reduces the amount of spatio/temporal diversity (only two sensors) needed to identify blindly TV channels and mitigate their effects using minimum mean-square error equalizers. Sensitivity to order and model mismatch have also been studied.

3. Space-Time Coded Multiple Access Communications

Transmit-antenna equipped with space-time (ST) coding has been researched recently in order to cope with performance and capacity limiting challenges arising with envisioned broadband wireless transmissions. The ST Generalized Multi-Carrier CDMA design that we derived relies on block spreading and multiple antenna transmissions to guarantee symbol recovery and diversity gains in frequency-selective propagation for both single-user and multi-user systems. To account for carrier offsets and Doppler-induced time-selective effects, ST double differential encoders/decoders are incorporated to achieve diversity gains without channel knowledge at both the transmitter and the receiver. In order to experimentally validate the proposed ST schemes, a software radio testbed is being implemented to serve as a key technology facility for near future broadband system development.

4. High-Rate Layered Space-Time Coding based on Linear Constellation Precoding (flat-fading channels)

Recent theoretical and experimental studies have shown that with affordable complexity, layered space-time (LST) transmissions can attain very high spectral efficiency when communicating through a flat-fading channel with rich-scattering. By incorporating linear constellation precoding into a judiciously designed LST structure, we developed a novel linearly precoded LST system, which allows for any number of transmit-and receive-antennas, and offers great flexibility in striking arbitrary performance-rate tradeoffs. Even with low-complexity sub-optimum decoding, our system enjoys considerable transmit diversity gains, and performs quite well from the viewpoints of both BER performance and mutual information. We also derived a sub-optimum decoder with complexity slightly higher than the nulling/cancelling algorithm used in V-BLAST. Ordering in the decoding algorithm was found to further improve performance. We designed systematically linear precoders to enable maximum diversity and coding gains per layer. We compared with competing alternatives and corroborated the unique merits of our algorithm.

5. Optimal Transmitter Eigen-Beamforming and Space-Time Block Coding (flat-fading channels)

Optimal transmitter designs obeying the water-filling principle are well-documented, and widely applied when the propagation channel is deterministically known, and regularly updated at the transmitter. Because channel state information is impossible to be known perfectly at the transmitter in practical wireless systems, we designed in this work an optimal multi-antenna transmitter based on statistical (mean or correlation) information about the underlying channels. Our optimal transmitter design turns out to be an eigen-beamformer with multiple beams pointing to orthogonal directions along the eigenvectors of the correlation matrix of the estimated channel at the transmitter, and with proper power loading across beams. The optimality pertains to minimizing a tight bound on the symbol error rate, which leads to better performance than maximizing the expected signal to noise ratio at the receiver. Coupled with orthogonal space-time block codes, two-directional eigen-beamforming emerged as a more attractive choice than conventional one-directional beamforming with uniformly improved performance, without rate reduction, and without essential increase in complexity. With multiple receive antennas and reasonably good feedback quality, the two-directional eigen-beamformer is also capable of achieving the best possible performance in a large range of transmit-power to noise ratios, without a rate penalty. We anticipate fundamental subsequent results based on this novel idea of optimally combining beamforming with space-time coding.

6. Space-Time-Frequency Coded OFDM (Frequency-Selective Fading Channels)

In this research thrust, we explored novel space-time-frequency (STF) coding for multi-antenna OFDM transmissions over frequency-selective Rayleigh fading channels. Incorporating subchannel grouping and choosing appropriate system parameters, we first converted our system into a set of group STF (GSTF) systems. This enabled simplification of STF coding within each GSTF system. We then designed criteria for STF coding, and exploited existing ST coding techniques to construct both STF block and trellis codes. The resulting codes turned out to be capable of achieving maximum diversity and coding gains, while affording low-complexity decoding. The performance merits of our design were confirmed by corroborating simulations, and compared with existing alternatives.

7. Optimum Training and Maximum-Diversity Transmissions (Doubly-Selective Channels)

High data rates give rise to frequency-selective propagation, while carrier frequency-offsets and mobility-induced Doppler shifts introduce time-selectivity in wireless links. To mitigate the resulting time- and frequency-selective (or doubly-selective) channels, optimal training sequences have been designed only for special cases: Pilot Symbol Assisted Modulation (PSAM) for time-selective channels, and pilot tone assisted OFDM for frequency-selective channels. Relying on our basis expansion channel model, we designed in this work low complexity optimal PSAM for block transmissions over doubly-selective channels. The optimality in designing our PSAM parameters pertains to maximizing a tight lower bound on the average channel capacity that is shown to be equivalent to minimizing the mean-square channel estimation error. It turned out that the optimal training strategy consists of equi-spaced and equi-powered pilot symbols surrounded by a number of zeros dictated by the channel's delay-spread, and inserted periodically with a period dictated by the channel's Doppler-spread. The design enabled a time-frequency sampling of the channel, and was shown to subsume training schemes for time- or frequency-selective channels as special cases.

Relying also on our basis expansion model of the doubly-selective channel, we also found that the maximum achievable multipath-Doppler diversity order is determined by the rank of the correlation matrix of the channel's expansion coefficients, and is multiplicative in the effective degrees of freedom that the channel exhibits in the time- and frequency-dimensions. Interestingly, it turns out that time-frequency reception alone does not guarantee maximum diversity, unless the transmission is also designed judiciously. We designed such block precoded transmissions that are equipped with time-frequency guards, and can be implemented efficiently by combining FFT operations with time-frequency interleavers. The corresponding

designs for frequency-selective or time-selective channels follow as special cases, and thorough simulations were performed to corroborate our theoretical findings.

Journal Papers (Total number of reporting work supported under this grant is **25**: Sept. 1998 – Dec. 2001)

Conference Papers (Total number **45**: Sept. 1998 – Dec. 2001)

List of Recent Journal Papers (2000 – 2001)

1. Z. Liu, X. Ma and G. B. Giannakis, "Space-Time Coding and Kalman Filtering for Diversity Transmissions through Time-Selective Fading Channels," *IEEE Transactions on Communications*, February 2002 (to appear).
2. Z. Liu, G. B. Giannakis and B. L. Hughes, "Double Differential Space-Time Block Coding For Time-Varying Fading Channels," *IEEE Transactions on Communications*, vol. 49, no. 9, pp. 1529-1539, September 2001.
3. Z. Liu, G. B. Giannakis, S. Barbarossa, A. Scaglione, "Transmit-Antennae Space-Time Block Coding for Generalized OFDM in the Presence of Unknown Multipath," *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 7, pp. 1352-1364, July 2001.
4. C. Tepedelenlioglu and G. B. Giannakis, "On Velocity Estimation and Correlation Properties of Narrow Band Communication Channels," *IEEE Transactions on Vehicular Technology*, vol. 50, no. 4, pp. 1039-1052, July 2001.
5. Z. Liu and G. B. Giannakis, "Space-Time Block Coded Multiple Access through Frequency-Selective Fading Channels," *IEEE Transactions on Communications*, vol. 49, no. 6, pp. 1033-1044, June 2001.
6. Z. Liu, G. B. Giannakis, B. Muquet and S. Zhou, "Space-Time Coding for Broadband Wireless communications," *Wireless Communications and Mobile Computing*, vol. 1, no. 1, pp. 33-53, Wiley, January-March 2001.
7. C. Tepedelenlioglu and G. B. Giannakis, "Transmitter Redundancy for Blind Estimation and Equalization of Time- and Frequency-Selective Channels," *IEEE Transactions on Signal Processing*, Vol. 48, No. 7, pp. 2029-2043, July 2000.

List of Recent Journal Papers Submitted (2000 – 2001)

1. Z. Liu, Y. Xin, and G. B. Giannakis, "Linear Constellation Precoding for OFDM with Maximum Multipath Diversity and Coding Gains," *IEEE Transactions on Communications*, submitted June 2001; revised December 2001.
2. S. Zhou and G. B. Giannakis, "Space-Time Coded Transmissions with Maximum Diversity Gains over Frequency-Selective Multipath Fading Channels," *IEEE Transactions on Information Theory*, submitted May 2001; revised December 2001.
3. C. Tepedelenlioglu, A. Abdi, and G. B. Giannakis, "Estimators of the Ricean K factor and Performance Analysis," *IEEE Transactions on Wireless Communications*, submitted December 2001.
4. S. Zhou, and G. B. Giannakis, "Optimal Transmitter Eigen-Beamforming and Space-Time Block Coding based on Channel Mean Feedback," *IEEE Transactions on Signal Processing*, submitted November 2001.
5. S. Zhou, and G. B. Giannakis, "Optimal Transmitter Eigen-Beamforming and Space-Time Block Coding based on Channel Correlations," *IEEE Transactions on Information Theory*, submitted October 2001.
6. X. Ma, G. B. Giannakis, and S. Ohno, "Optimal Training for Block Transmissions over Doubly-Selective Wireless Fading Channels," *IEEE Transactions on Signal Processing*, submitted October 2001.

7. Z. Liu, Y. Xin, and G. B. Giannakis, "Space-Time-Frequency Coded OFDM over Frequency-Selective Fading Channels," *IEEE Transactions on Signal Processing*, October 2001.
8. X. Ma and G. B. Giannakis, "Maximum-Diversity Transmissions over Doubly-Selective Wireless Channels," *IEEE Transactions on Information Theory*, submitted September 2001.
9. Y. Xin, Z. Liu, and G. B. Giannakis, "High-Rate Layered Space-Time Coding based on Linear Constellation Precoding," *IEEE Transactions on Communications*, submitted September 2001.
10. G. Leus, S. Zhou, and G. B. Giannakis, "Multiple Access regardless of Time- and Frequency-Selective Fading," *IEEE Transactions on Information Theory*, submitted June 2001.
11. Z. Liu, Y. Xin, and G. B. Giannakis, "Linear Constellation Precoding for OFDM with Maximum Multipath Diversity and Coding Gains," *IEEE Transactions on Communications*, submitted June 2001; revised December 2001.
12. Y. Xin, Z. Wang, and G. B. Giannakis, "Space-Time Diversity Systems based on Linear Constellation Precoding," *IEEE Transactions on Wireless Communications*, 2002 (to appear).